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EXTENDED STATEMENT ON WEATHER MODIFICATION

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EXTENDED STATEMENT ON WEATHER MODIFICATION

PREFACE

Discussion of ways of deliberately changing the weather to benefit mankind has been going on for a very long time. However, it is only in the last few tens of years that practical means have become available which may make this possible. Suggestions have been put forward from time to time with a view to modifying climate over larger areas of the globe. This document does not discuss such concepts: rather it deals with processes likely to affect weather over much more limited areas, typically ranging from a few thousand to a few tens of thousands of square kilometers. Further, it deals for the most part with techniques which affect the microphysical processes in clouds and which have been tried repeatedly in the field, often with considerable success.

The Seventh Congress of WMO in April-May 1975 issued a Statement on the "Present State of Knowledge and Possible Practical Benefits in Some Fields of Weather Modification". The present document expands on that statement and includes any additional information which has become available since 1975. It is divided into largely self-contained sections each of which lists a series of references from which the interested reader may find greater detail should he need it. The original 1975 Statement is included with this document for completeness.

PRECIPITATION ENHANCEMENT

1. INTRODUCTION

As is well known, a cloud forms when moist air is cooled below its dew-point and condensation takes place upon sub-microscopic hygroscopic particles which are almost always present in abundance in the earth's atmosphere. The cooling, of course, may be the result of radiation to space, of convective ascent of buoyant air masses originating as cool air moves over a warm surface, of meso-scale or synoptic-scale motions which produce widespread lifting, or of the mixing of two air masses at different initial temperatures and humidities.

As the cloud grows, the droplets increase in size and, even if they formed initially on nuclei of quite different size, tend towards a single radius which increases with height above cloud base. Particularly if there are very large concentrations of condensation nuclei, and hence of cloud droplets, the resulting cloud is likely to be colloidally stable and no precipitation may result even if the cloud grows quite large. Such clouds often form, grow and evaporate over inland areas without producing any significant rain. However, if the concentration of droplets is relatively low and there are a few giant nuclei resulting in a few much larger than average droplets, both of which conditions are common in clean maritime air, the larger droplets will fall and grow by collecting the smaller ones in their path. Provided the cloud is deep enough, they will grow to sufficient size to fall to the surface as rain.

If the cloud grows tall enough to exceed the height of the freezing level the droplets will normally supercool, and indeed this supercooling can occur in natural clouds down to temperatures of -20C or even -30C. Ultimately, however, and always before they reach a temperature of -40C, the droplets will freeze. Alternatively, ice crystals may form directly from the vapour upon small particles called freezing nuclei which are quite different in nature from the condensation nuclei mentioned above. As soon as ice particles of any form appear in the presence of supercooled water droplets, the cloud becomes colloidally unstable because the saturation vapour pressure over ice is less than that of water at the same temperature and hence ice particles grow rapidly at the expense of the water droplets. As long as the concentration of ice particles is small in comparison to that of water droplets, the former will grow quite large by this process and commence to fall, collide with and collect the water droplets and other smaller particles in their path. Again, provided the cloud depth is sufficient, the particles will grow large enough to precipitate to the surface.

These two natural precipitation processes are of immediate interest to the weather modifier because, by adding quite small concentrations of giant condensation nuclei or of ice nuclei to clouds where their absence or low natural concentrations prevents or renders inefficient the development of precipitation, it is often possible to augment the amount of precipitation which would otherwise occur. The ice crystal process is of particular interest in the case of clouds forming in continental air where the high concentration and small size

of the cloud droplets would result in a colloidally stable situation with little or no precipitation.

There is a third situation which is of interest from the viewpoint of weather modification. This is when a convective cloud becomes significantly supercooled but where its growth is limited by atmospheric stability conditions and where comparatively small increases in cloud buoyancy could result in considerable growth of the cloud. Taller clouds are, of course, inherently capable of producing greater precipitation than smaller ones having the same base levels so that if growth can be encouraged there is reason to expect greater precipitation. In such growth-limited supercooled clouds where the concentration of natural ice nuclei and resulting ice crystals is not excessive, the addition of very large numbers of artificial ice nuclei in the upper levels can result in complete glaciation of substantial regions of supercooled water. The release of the latent heat of freezing can produce sufficient buoyancy to produce considerable cloud growth and significant increases in precipitation over what would have occurred naturally.

These three mechanisms have all been explored with varying degrees of success and the results of typical experiments are described below. It is important to bear in mind the fact that useful precipitation can only result from experimentation if clouds suitable to the seeding techniques are present in reasonable abundance and are deep enough to ensure that any precipitation which forms will not undergo significant evaporation before reaching the surface.

It is equally important to realize that experience shows that on average the increases that can be expected from precipitation enhancement techniques are relatively modest and are often well within the natural variability of the precipitation it is hoped to change. Hence quite sophisticated statistical techniques are essential to determine whether any changes in precipitation which are observed are associated with the modification treatment or merely part of the natural fluctuation. Further, extensive physical measurements are necessary to document the existence of a cause-and-effect relationship between the treatment and the observed changes.

2. WARM CLOUDS : THE COLLISION-COALESCENCE PRECIPITATION PROCESS

General Principles

In tropical or semi-tropical countries many of the potential rain-producing clouds are convective in nature and their tops often do not exceed the height of the freezing level. This is particularly true in conditions when little natural rain falls and there is the greatest interest in precipitation enhancement. Hence, the possibility of increasing rainfall by enhancing the efficiency of the collision-coalescence process is of considerable concern.

When moderately deep clouds develop whose tops do not significantly exceed the height of the freezing level, it may sometimes be possible to initiate or enhance the effectiveness of the precipitation

process by seeding them with water droplets or hygroscopic particles. Only a limited number of experiments have been carried out to test the effectiveness of the technique because, a priori, it is clear that large masses of seeding material are necessary. Thus, if we consider the seeding to be carried out with 10 μm diameter salt particles of density 2 g cm^{-3} and that each particle ultimately grows to a 2.5 mm diameter raindrop, we can readily calculate that the original particle has increased in mass by a factor of nearly 10^7. One mm of rain over an area of 1 000 km^2 has a mass of 10^9 kg so that if this were due to seeding it would have been necessary to employ 100 kg of seeding material. Even for this small result, it has been necessary to assume a more favourable growth ratio than is likely to occur in practice. However, the situation would be much more favourable if a "chain reaction" occurred, such as that postulated by Langmuir (1948), in which drops break up after first growing by coalescence to a large enough size and the fragments then serve as growth centres for new large droplets. However, little evidence exists that such a process occurs in natural clouds. In spite of these limitations, a few encouraging but not conclusive experiments have been carried out.

Caribbean and Central USA

Possibly the earliest attempt to produce rain from warm clouds was that of Braham et al (1957) in which up to 400 gallons of water was released from an aircraft into the tops of individual clouds. In each case the seeded cloud was chosen at random from a pair of essentially similar clouds and the differences studied between the behaviour of each cloud of the pair. In all, or nearly all, cases both treated and un-

treated clouds produced rain some time after they were first examined; however, the treated clouds rained much earlier than those un-treated although the amount of rain they produced appeared the same. Thus the experiments seemed to demonstrate that seeding could stimulate the coalescence process but did not give much encouragement to the use of the technique on a practical basis.

Puerto Rico

Howell and Lopez (1966) carried out a limited number of seeding experiments in southern Puerto Rico in which they distributed 30 μm diameter dry salt particles or brine droplets from an aircraft. On the basis of comparisons with historical rainfall records they concluded that the seeding caused increases of up to 14% rainfall but the result was only marginally statistically significant at about the 0.10 level.

India - Delhi, Agra and Jaipur

Indian workers have carried out by far the greatest number of salt seeding experiments aimed at increasing precipitation from convective clouds. Biswas et al (1967) report the results of three long-term programmes, one of 8 years, one of 6 years and one of 4 years duration. They used common salt as a seeding material, ground to a median particle mass of about 10^{-9} g (i.e. 10 μm diameter) dispersed from the earth's surface by blowers at a rate of about 2.5 kg min^{-1}. All experiments were randomized with upwind control areas and showed increases in precipitation associated with the seeding, though that for the shortest experiment was

not statistically significant. For the other two experiments increases in excess of 40% were claimed at statistical significance levels of about 0.01 to 0.07, depending upon the type of statistical significance test employed. In spite of these apparently very favourable results, India does not appear to have put the technique into operational use and workers there continue to experiment and report their research results - which, however, appear less promising than in the case of the earlier work.

South Dakota

Dennis and Kozcielski (1972) carried out seeding experiments on convective clouds in South Dakota in which relatively large salt particles (a 50-50 mixture of 25 μm and 150 μm median mass-diameter particles) were dispersed from aircraft. They report statistically significant differences in the development of precipitation between seeded and unseeded clouds as detected by radar but do not comment upon whether or not the seeding produced increased precipitation.

3. COLD CLOUDS - THE ICE CRYSTAL PRECIPITATION PROCESS

A. SEEDING FOR MICROPHYSICAL EFFECTS

General principles

In the most commonly employed technique for seeding cold clouds (i.e. those rising well above the height of the freezing level), moderate concentrations of ice forming nuclei have been introduced in order to stimulate or enhance the efficiency of the microphysical process described earlier in the Introduction. As the simplest possible hypothesis of the effect of seeding, it might be assumed that one ice nucleus produces one

raindrop. Depending upon the seeding material employed and the temperature level at which it is introduced or becomes effective, one gram of material may result in the production of 10^{12} to 10^{15} ice nuclei. Hence, if each nucleus results in the formation of a 2.5 mm diameter raindrop, less than 100 g, and possibly less than 0.1 g of material could suffice to produce 1 mm of rain over an area of 1 000 km^2. Because of this fact, and because in other than tropical areas a very large proportion of rain-producing clouds are supercooled, it is easy to see why this seeding technique has attracted the greatest number of attempts at precipitation enhancement.

Early History

Attempts to modify supercooled clouds to produce extra precipitation commenced almost immediately after Shaefer (1946) demonstrated in the laboratory that small fragments of dry ice dropped into a supercooled cloud produced vast numbers of ice crystals which grew and fell to the bottom of the cloud chamber. Most of the early experiments were carried out without adequate statistical control or understanding of all the complexities of the process which have later become apparent, and little comment can be made about their results. Many commercial operators commenced cloud seeding as a business, again often without any serious attempt being made to determine whether or not the seeding really increased rainfall. However, by the middle 1950's most Government and University projects and the better projects run by private operators were using randomization techniques in order to obtain proper statistical control.

from individual bands to storm systems as experimental units with all bands within a 48 hour storm period either seeded or not according to random selection. It was claimed that regions of the target area experienced enhanced precipitation with seed/not seed ratios in excess of 1.5 at statistical significance levels of 0.05 or better. For the second phase of the experiment the effects of seeding seemed to be greatest when the 500 mb (cloud top) temperature was between about -17 and -20C.

For the first phase this relationship was not so clearly defined but similar tendencies were detected. The convective bands appeared to widen and possibly slow down after seeding, indicating that much of this increase in precipitation was due to a change in the duration of band precipitation rather than an increase in its intensity.

Climax

The third project which underwent two phases was carried out in the winter seasons of 1960 - 1965 and 1965 - 1970 in the vicinity of Climax in the Central Colorado Rockies. These randomized seeding experiments, Climax I and Climax II respectively, are reported by Grant and Mielke (1967), Grant et al (1971), Grant and Kahan (1974) and Chappell (1971). Here the experimental period was 24 hours and a day was included in the randomized sequence if precipitation was forecast for a station upwind of the site. Ground-based generators burning silver iodide were employed. A microphysical model indicated the likelihood that seeding should increase precipitation drawing upon surplus condensate

released by orographic lifting. The results suggest increases in precipitation, the magnitude of which was dependent upon the temperature at the 500 mb level with the most significant effects when this temperature was between -20 and -11°C. The increase was also dependent upon the wind speed near cloud base - i.e. the rate at which condensate should have become available - with peak increases when the wind speed was between 12 and 14 m s^{-1}. It was estimated that for a full winter season it should be possible to increase precipitation by about 1.5 to 2.4 ins or 11 to 17%. The results of the second 5-year experiment appeared to strongly confirm the findings of the first experiment.

Colorado River Basin

Because of the apparent success of the Climax experiments, an experiment was initiated in the San Juan Mountains of Colorado (reported by Elliott et al (1978)) to see whether the experimental procedure applied at Climax would be effective in an operational mode. Again, the experiment was randomized by the day but here no significant difference in precipitation was detected as between seeded and not seeded days. However, a posteriori analysis based upon 6-hour time blocks indicated that positive effects might have occurred during periods of relatively warm cloud top temperature as expected from the Climax results.

Tasmania

A further long-term randomized experiment was carried out between 1964 and 1970 over the catchment area of a hydroelectric

authority in Tasmania. As reported by Smith et al (1979) there were 54 seeded and a similar number of unseeded periods each of 10-18 days duration (change of period occurred in fine weather) with the experiment running only on alternate years. Seeding with silver iodide smoke was carried out from aircraft either at cloud base or at the -5°C level or above, depending upon cloud type. Results were analysed separately season by season. The authors concluded that seeding increased autumn rainfall by 20-40%, significant at the 0.02 - 0.04 level, that the winter rainfall increased by about 10%, significant at about the 0.1 level but that any changes during spring or summer were not significant.

Overall assessment

To assess the significance of these experiments it is useful to turn to the Report of the Statistical Task Force to the Weather Modification Advisory Board (1978). This report notes that recent re-analyses of the Climax data have cast some doubts on the results - an issue which is not yet fully resolved. For the other experiments described above, the Report notes that the second Israeli experiment can be regarded as possible reconfirmation of an already successful experiment, the Santa Barbara and Tasmanian experiments are regarded as close to persuasive in their claims of success, while the need for post hoc categorization of experimental days in the Colorado River Basin experiment leave the possible strength of evidence in some doubt.

B. SEEDING FOR DYNAMIC EFFECTS

General Principles

It was noted very early in the experiments in which cumulus clouds were seeded that occasionally marked growth occurred. However, it is only comparatively recently that deliberate attempts have been made to cause such growth by massive seeding of convective clouds with a view to obtaining greatly enhanced precipitation. The physical principle on which the experiments are based is simply that when large quantities of supercooled water can rapidly be caused to freeze, the release of the latent heat of freezing will produce sufficient buoyancy to enable the cloud to grow much taller than would otherwise be the case. Greater cloud depth will in turn allow greater growth to take place on precipitation particles, longer cloud lifetime and more precipitation.

Florida Area Cumulus Experiment (FACE)

In this experiment individual cumuli forming over an area of about 10^4 km^2 were seeded by dropping pyrotechnic flares containing large quantities (100 - 1 000 g per cloud) of silver iodide into the upper levels of active supercooled clouds on days for which a simple numerical model suggested that such a procedure would result in significant cloud growth. The experiment was complicated by many changes in seeding techniques and method of analysis, as might be expected in an exploratory experiment. Simpson and Dennis (1974) and Simpson and Woodley (1975) claim that significant increases in precipitation were obtained, particularly in cases where merging of adjacent clouds followed seeding. Woodley et al

(1976) report the use of more efficient pyrotechnic devices in 1975 and give the results of further statistical analyses. For certain methods of analysis and certain categories of clouds (as defined by whether or not their radar echoes showed significant motion) positive, statistically significant effects are reported.

North Dakota

This project was conducted in the summers of 1969-1972 and was intended to test the effects of seeding upon both rainfall and hail. The seeding rate was adjusted from 10 or 20 g of silver iotide for rain stimulation from small cumuli to coninuous seeding rates exceeding 1 kg hr^{-1} for hail suppression if the project meteorologist judged a storm to be approaching hail intensity. The experiment was randomized with 25% of days reserved as not-seeded days. The analysis of the results suggested that on days on which a cloud model predicted dynamic growth would follow seeding there was a significant increase in frequency of rain events as well as an increase in actual rainfall in the target area.

Overall assessment

The report of the Statistical Task Force to the Weather Modification Advisory Board (1978) in its assessment of these two projects notes that because of a variety of statistical issues and due to subjective influences, the conclusions must remain in doubt.

4. EXTRA AREA EFFECTS

A major concern in all cloud seeding projects is whether enhancement of precipitation in the specified target area is at the expense of that "downwind" or whether the seeding results in an overall increase in the efficiency of the precipitation process. Many studies have been made of the problem but it is beset with difficulties and no generally accepted conclusion has been reached. Certainly, a number of reports purport to show increases well outside as well as inside the target area, but in the absence of a convincing physical mechanism, as well as strong statistical evidence, one can only regard the whole issue with caution. The subject is reviewed in PEP Report No. 6 (WMO 1977) and some comments are made in the Report of the Statistical Task Force to the Weather Modification Advisory Board (1978). Both reports give extensive references to the subject.

5. CONCLUSIONS

Of the many large-scale area experiments (order of 10^3- 10^4 km^2) in which moderate concentrations of artificial ice nuclei were dispersed in clouds, only a few have demonstrated at a satisfactory statistical significance level that seeding increased precipitation. The increases in precipitation were typically 10-20% when averaged over the target area for the full operating season. In many experiments no statistically significant increases were observed and in a few experiments there appear to have been decreases in precipitation following seeding.

These apparently contradictory results may well relate to the fact that clouds which are supercooled to the same extent but which have different microstructures and different ice budgets could be expected to respond in a different manner to a given seeding technique. The high colloidal stability of the winter stratiform clouds in Tasmania and of the winter orographic clouds in central USA and the winter "continental" cumuli of Israel seem to render these clouds more favourable to seeding for microphysical effects than is true for maritime cumuli. These latter clouds have been found to produce naturally high ice particle concentrations at some stage in their life cycle and it may well be that the addition of additional ice nuclei would be detrimental, resulting in either no change in precipitation or possibly a decrease. It now seems that the water-ice budget of the clouds is probably one of the more crucial factors governing the release of precipitation. Thus it is in those cases when the processes of ice nucleation and particle growth are less than the rate at which moisture is released in the clouds by the updraft that seeding can be expected to produce positive effects.

There is evidence that the effect of seeding is dependent on seasonal as well as geographic factors. In some experiments evidence has been found to suggest that the overall results are influenced by combination of positive and negative effects, presumably because of the variability in cloud conditions throughout the experiment. Statistical evidence is accumulating about the existence of downwind and extra-area effects but so far neither this evidence, nor the physical hypotheses put forward to account for the effects, can be regarded as conclusive.

Cloud seeding for dynamical effects also appears promising but far fewer experiments have been carried out. So far it has not been demonstrated satisfactorily that the techniques can produce useful increases in precipitation over a large area although the effect on individual cumuli is well documented.

The seeding of warm clouds with water sprays or hygroscopic nuclei has received comparatively little attention, probably because of the larger quantities of seeding material required. Some promising results have been achieved but, in most cases, the experimental results have been inconclusive.

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DISSIPATION OF FOG

INTRODUCTION

Fogs are traditionally classified according to the cause of their formation; however, from the standpoint of dispersal it is more relevant to classify them according to their constitution and temperature, since the method of modifying them depends upon these factors rather than the fog's origins.

Ice fog is a suspension of small ice particles generally only occurring at temperatures less than -30°C. Studies of this fog have been made by Ohtake (1970) in Alaska in the 1960's and in early 1970 which have resulted in some practical recommendations on decreasing its occurrence by minimizing the production of moisture from human activities. However, no practical method has yet been found for modifying an ice fog once it has formed.

Supercooled fog is composed of water droplets which remain unfrozen although their temperature is below 0°C. Provided the temperature is not too low and there is a relative absence of ice nuclei to stimulate freezing, such fogs are naturally stable. They can be modified quite readily by introducing artificial ice nuclei.

The third type of fog, warm fog, consists of water droplets at above freezing temperature. It is the most common type of fog and is difficult to disperse artificially: nevertheless, a number of methods have been developed which are successful.

HISTORICAL BACKGROUND

Some of the earliest technically sound weather modification efforts dealt with the clearing of fog. In the 1930's Houghton and Radford (1968) studied the properties of sea fog, explored various modification concepts and developed one system to the point of successful demonstration. The technique developed, which involved seeding with hygroscopic chemicals, was not pursued further at the time since there seemed to be other, more attractive, ways of solving the major operational problems - mostly associated with aviation interests - caused by fog.

Except for a period during World War II when the British developed a thermal dissipation system "FIDO" (Walker and Fox (1946)), a system which would be far too expensive and hazardous to use in peacetime, the major efforts to solve aircraft operational problems caused by fog have concentrated on improving electronic blind-landing systems. In the 1960's and 1970's, however, several sophisticated warm fog modification systems were developed and reached the prototype testing stage with some success (Fletcher (1971)) and one system has been operational since 1970.

The demonstration by Schaefer (1946) that clearings could be made in supercooled stratus clouds by introducing dry ice, i.e. solid CO_2, into the clouds marked the beginning of a rapid expansion of the field of weather modification. This event also introduced new modification concepts for fogs that were supercooled. By the early 1960's many systems for clearing supercooled fogs by seeding with dry ice or other ice crystal nucleating agents were being adopted operationally. By the 1970's supercooled fog was being cleared operationally in the USA, France, USSR and Germany (Fletcher (loc. cit.), Silverman and Weinstein (1974)).

RECENT PROGRESS

Experimental techniques for determining whether or not, and to what degree, natural fogs can be modified are considerably simpler than is the case for almost any other weather phenomenon. In general, weather modification involves "weather" that has a very complex structure which is often continually changing and involves many physical and dynamical processes which interact over a wide range of scales. The experimentalist must lean heavily upon statistical techniques to be able to derive credible answers from his field experiments. In contrast to this situation, it is comparatively straightforward to determine the degree of modification of fog or stratus clouds resulting from field experiments. The particular fog or stratus chosen for an experiment must, in the unmodified state, have properties that are relatively

constant and the modification produced (e.g. an increase in visibility) must represent a large change from natural conditions. Since both these conditions often apply a few experiments involving a limited number of measurements can often give definitive answers.

WARM FOG

A large number of processes have been suggested for modifying warm fog. Only the more successful are described below.

Considerable effort has been devoted by many groups to the development of fog dissipation techniques based upon seeding with hygroscopic chemicals. The basic idea is that if hygroscopic substances in the form of either dry particles or solution droplets are released within a fog they absorb water vapour and the air, in drying, causes the fog droplets to evaporate. The hygroscopic particles themselves grow large enough to precipitate out of the system. Kunkel and Silverman (1970), for example, have explored the best chemicals to be used for this purpose and have considered methods of encapsulation of the material. Similarly Silverman and Kunkel (1970) have used theoretical models to determine the optimum particle size and seeding strategy. Many such similar studies have been made. Environmental considerations are also of major importance in hygroscopic seeding, since large quantities of material may be necessary which ultimately is precipitated to the surface, and encapsulated urea has been put forward as the optimum choice.

Successful development of a seeding agent and its use in small-scale field trials has not yet been followed by similar success over a large airport runway. Delivery of the seeding material at the right time and place to effect clearing more-or-less continuously of a runway some distance downwind from the seeding line has not proved reliable. More widespread seeding, which might be effective in clearing the fog, is economically not practicable.

Another method that has been developed for clearing warm fog involves mixing of the relatively dry air often found above radiation fogs or stratus decks down into the fog or cloud layer. The method has been described by Plank (1969), Plank and Spatola (1969), Plank et al (1971) and Plank (1971) and involves the use of the downwash from a large helicopter stationed just above the top of the fog. It has successfully created holes and clear lines in fogs up to 100-150 m. thick. It has had operational success in special circumstances, such as helicopter rescue and supply operations in which the helicopter is able to land through a hole in the cloud which it has cleared for itself.

At the present time the only major warm fog dissipation technique being used operationally is the thermal system in which sufficient thermal energy is used to evaporate the fog droplets and to raise the temperature of the air sufficiently to accommodate the additional water. As described by Sauville (1976) this system is in use in France at Orly and Charles de Gaulle airports. It was used to assist aircraft landings for some 150 operations in 1977/78 and for some 250 in 1978/79. The development of this sytem has had a long history from the days of "FIDO" through small-scale experiments using jet exhausts to sophisticated large-scale installations. Operational systems involve large, permanent, expensive installations, they consume large amounts of fuel and are practical for only the busiest and largest airports where fogs are common occurrences. In addition to the two French installations a prototype system, described by Kunkel (1979), has been constructed in the USA, after extensive small-scale testing and engineering trials. A key attribute of this new system is the use of propellors to distribute the heated air. Another new system has been developed in West Germany using the thermodynamic principle of a heat pump. Air is first cooled and some of the fog and condensed water are mechanically separated from the air; the air is then reheated

using heat generated in the refrigeration system. This system requires a very large amount of electrical power but no extra water is generated as is the case with systems burning fossil fuels. A prototype of this system has been developed and initial tests in 1974 gave encouraging results. It is environmentally acceptable but, as is also true of the US system, the complex installation requirements, the high capital - and operating-costs have so far discouraged its development beyond the prototype stage.

Fog dissipation methods based upon the use of artificial electrification to increase the natural rate of coalescence and precipitation of fog droplets or the use of laser heating have not so far led to practical applications.

SUPERCOOLED FOGS

The dissipation of a supercooled fog is achieved by seeding it with material which produces ice crystals which, because of the difference in vapour pressure over ice and water at the same temperature, grow by deposition of vapour supplied by the fog droplets which thereby decrease in size. The reduction in fog droplet size itself increases the visibility but the main effect occurs when the ice crystals grow to such a size that they fall out. While the physics of the process has some similarities to that in which hygroscopic particles are used to clear warm fogs it is much more effective in that orders of magnitude less material is required to form effective ice crystal nuclei than to form effective hygroscopic growth centres.

A number of operational procedures for clearing supercooled fog have been developed, including seeding from an aircraft with dry ice or silver iodide or from extensive ground installations in which the expansion of propane gas produces sufficient cooling to generate large quantities of ice crystals (Fletcher (loc. cit.), Serpolay (1960), Rabbe (1969)). These methods of modifying supercooled fogs are in fairly wide use today, but are limited to the relatively few regions of the world where supercooled fog is a sufficiently important operational hazard. Operational clearing is conducted in France, Germany and Norway as well as in the USA and USSR.

The success achieved in clearing supercooled fog is paralleled by similar clearing of supercooled stratus decks. Much work has been done, for example, by Vickers and Church (1966), Dyer and Kunkel (1978), and Dyer et al (1977), and clearing of large regions of such decks appears quite feasible; however no operational use has been made of the technique to date.

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Further, in many projects considerable efforts were being made to document the physical changes taking place in seeded clouds and comparing them with what happened in otherwise similar but unseeded clouds.

It would be impossible to review here the very many precipitation enhancement projects which have been carried out throughout the world in the past few decades. As an alternative, this discussion will be limited to the recent projects carefully reviewed by the Statistical Task Force of the US Weather Modification Advisory Board (1978). Of the seven precipitation enhancement projects reviewed, five were not dependant upon dynamic effects for their effectiveness and of these five, three had each undergone two phases of long-term experimentation.

Israel

The first Israeli experiment commenced in February 1961 and continued in all subsequent winter seasons until the spring of 1967. A cross-over design was employed in which either a northern area or a southern one was seeded on a random basis with a buffer zone in between never being seeded. Seeding was from an aircraft flying just off the coast, dispersing silver iodide smoke into the bases of the clouds which approached from the west. The primary aim was to put extra rain into the catchment area of Lake Tiberias which is in the centre of the northern target area. An increase in rainfall of 15%, significant at about the 0.05 level, was achieved over the whole target area with greater and more significant increases in the interior region of the northern area. In

the second Israeli experiment, which ran from 1969 to 1975, the seeding line for the northern area was moved inland somewhat, allowing a control area to be available for statistical analysis. Using this control area in a preliminary analysis, Gagin and Neumann (1974, 1976) deduce that an increase of the order of 15%, significant at better than the 0.05 level, occurred in the northern target area. The increase was found to be greatest when cloud top temperatures were between -12 and -25C. No conclusive result has been reported for the southern target area.

Santa Barbara

A long series of experiments was carried out near Santa Barbara in Southern California in which the winter cyclonic storms were seeded to produce extra precipitation. The first series of experiments ran from 1957 to 1960 but its results were inconclusive. In the second series of experiments during the winters of 1967/68 - 1973/74 convective rain bands, identified by radar and confirmed by the presence of surface precipitation were seeded according to random selection. During the first phase of this experiment, reported by Elliott et al (1971), all seeding was conducted at a single fixed point atop a 1 000 m ridge NW of Santa Barbara, using pyrotechnic devices containing silver iodide which were released while a convective band was overhead of the seeding site.

In the second phase of the experiment from 1970-1974, reported by Brown et al (1976), the seeding was done from an aircraft operating about 60 km west of the former seeding site and randomization was changed

HAIL SUPPRESSION

1. Introduction

Worldwide losses of agricultural production due to hail damage are estimated to be in excess of 2×10^9 dollars annually. However, in contrast to other weather-related disasters such as drought, floods, hurricanes etc., hail losses tend to be very localized and whilst crops in a small region can be completely destroyed, nearby crops remain unscathed. It is this local nature of hail damage, causing as it does undue hardship on the minority, that generates such intense interest in possible methods of hail suppression.

The interest in hail suppression is worldwide as shown by the results of a survey conducted by WMO in 1972. The responses indicated that at least 34 countries actually undertook or were interested in undertaking, experiments in hail suppression, and another 32 were involved in, or were actively planning, scientific studies in this field.

At the same time, hailstorms are very complex meteorological phenomena which have extreme variability in time and space and this makes it very difficult to assess the results of any programmes aimed at their modification, whether they are scientific experiments or operational projects. Several efforts in operational hail suppression have been carried out over the last three decades, some on a very large scale and with the full support of the agricultural community. However, because

of the fundamental difficulty of evaluation, it has not been possible to provide any unambiguous scientific assessment of the true effectiveness of such programmes. On the other hand, the few large-scale randomized scientific experiments undertaken have all produced inconclusive results; after exhaustive analysis no statistically significant effects of seeding were detected in any of the hailfall characteristics determined either by ground or radar measurements.

2. Hail suppression hypotheses

Many hypotheses have been proposed for suppressing hail. The five that have received widest discussion are:

(i) Enhanced competition among hailstone embryos;

(ii) Glaciation of medium on which hailstones grow;

(iii) Lowering of trajectories of growing hailstones;

(iv) Promotion of coalescence, followed by freezing; and

(v) Dynamic effects, e.g., destruction of cumulonimbus clouds by initiation of downdraughts.

Glaciation, meaning conversion of supercooled cloud water to cloud ice, requires unrealistically large amounts of

ice nucleating agents, while the trajectory lowering and promotion of coalescence concepts need very large amounts of hygroscopic material. Dynamic effects, while potentially very important, have not been sufficiently studied to yield a useful working hypothesis.

This leaves enhanced competition among hailstone embryos as the only hypothesis which is generally accepted as showing promise for success based on the current understanding of hailstorms. This hypothesis, known as "beneficial competition" or "competing embryo", can be simply stated as follows:

"If the number of growing hailstone embryos can be increased by a large factor (> 100), then the competition for the available water supply prevents any embryos from growing large and thus the resulting hailstones either melt before reaching the ground or are too small to cause any damage".

To implement this hypothesis it is necessary to increase the concentration of hail embryos in the hail growth zone. Any large frozen hydrometeors could function as hail embryos. When large supercooled raindrops are present, on freezing these would yield very efficient hail embryos. In hail clouds, where the coalescence process is not operating, the competition concept could still be implemented by increasing the concentration of graupel at an early stage in the life of the cell. The possibility of successfully

modifying storms by introducing additional competing embryos is undoubtedly related to the local circulation in the storm and to the manner in which the individual storm cells develop. For example, supercells which are responsible for a large percentage of the damage in some regions are believed, by some persons, to be particularly difficult to modify sucessfully.

In order to implement the "competing embryo" hypothesis by means of seeding with ice nuclei it appears that the production of additional hail embryos to compete with the natural embryos for the available supply of supercooled water in the hailstone growth region is the most promising approach at this time. In this case the seeding agent must act when and where the embryos form, and this may be at some distance from the hailstone growth region.

3. Outstanding scientific problems

During the last decade, systems for observing hailstorms have improved dramatically with the advent of such tools as polarizing, doppler and multi-wave-length radars; storm penetrating instrumented aircraft and automated ground meso-meteorological networks. At the same time, the capability to monitor storms with radar and to identify potential, or producing, hail cells using real-time mini-computer processing techniques, together with the wide range of cloud seeding devices now available, provides the technical capability to deliver seeding material where, when, and in the concentration desired.

This technical capability has advanced more rapidly than the understanding of hailstorms and the field of hail suppression has thus reached the point where further significant advances in application must await the resolution of several scientific problems.

3.1 Forecasting hail occurrence

Skilled forecasting of natural hail occurrence is obviously needed for the selection of experimental days in any suppression experiment; the more accurately hail can be forecast, the more economically and effectively can the experiment be conducted. Operational work on hail suppression makes use of daily hail forecasts, which are based on physical concepts of the mechanism of hail formation and on statistical methods, taking account of several parameters of the atmosphere which characterize convective instability, humidity and wind conditions in the atmosphere. The forecasts are based on rawinsonde data and synoptic maps. In some regions, forecasts are supplemented by satellite and radar information. Forecasts typically cover a six-hour period for which a success rate of 80 per cent, or better, has been claimed in some situations. Forecasting the location of the region where the hail forms, and forecasting the intensity of the process, is a more complex and difficult, although important, task. The development of intensive hail processes is favoured by an increase in atmospheric humidity and convective instability with moderate wind shear. There are indications that the region where the hail forms is related to meso-scale and

synoptic-scale forcing processes, such as low-level convergence or high-level divergence.

The variations in hail and storm characteristics from one cell to another, or from one day to another, are so large that it is difficult or impossible to demonstrate any effect of seeding at an acceptable level of significance, unless a very high degree of suppression is achieved, or unless predictor variables and other evaluation criteria can reliably be provided through forecasts.

3.2 Hail microphysics

Damaging hail results from the natural introduction of solid embryos into regions with appreciable concentrations of supercooled water and updraughts sufficiently strong to support the growing hailstones. It is thought that the regions of embryo formation are sometimes distinct from the region of growth of large hail.

The most favourable regions for rapid growth of large hailstones are those with moderate to strong updraughts (> 12 m sec^{-1}), appreciable liquid water concentrations (> 2 gm^{-3}), and low temperatures (< -15°C). Embryo formation on the other hand is favoured by weaker updraughts, say 5 m sec^{-1}. In much stronger updraughts, newly formed ice particles would be carried up to the cloud top before growing large enough to become hail embryos.

Two types of embryos have been distinguished. One type results from the freezing of supercooled raindrops, the other from the growth of graupel. Which type predominates in a storm presumably depends upon cloud-base temperature, updraught speed, liquid water concentration, cloud droplet size spectrum and activity of the ice nuclei which are present.

Only in a few places have a sufficient number of hailstone samples been collected and analysed to provide any meaningful data on the frequency of occurrence of different types of hailstone embryo and wide variations are found. In all regions there is a higher percentage of frozen-drop embryos found in the large stones compared to the small stones.

Therefore, in designing and applying a hail suppression technique, more information is required concerning the nature of the hail embryos, the manner in which these are introduced into the region of stone growth and on the conditions in this region of growth.

Nearly all hail suppression projects rest upon the assumption that hail is due, at least sometimes, to a deficiency of natural ice nuclei in the atmosphere. Nevertheless, no correlation between hail occurrences and variations in the concentration of natural ice nuclei, which often vary by a factor of ten or more, has been noted. While it is still possible that there is a threshold concentration required to suppress hail, the threshold (if it exists)

probably exceeds the maximum observed concentration of natural ice nuclei. Therefore, if hail processes are to be modified by addition of ice nuclei, the concentration of artificial nuclei must be larger than the typical concentration of natural ice nuclei by a large factor, of perhaps 1 000. Such changes have in fact been produced.

3.3 Storm macrophysics

The evolution of precipitation particles, such as hailstones within a storm, is determined by the properties of the local environments through which they are transported. In turn, their trajectories are determined by the interplay between the storm-scale air motions and the terminal velocity of the particles. Thus, the later stages of hailstone growth must occur in strong updraughts, while the earlier stages - the formation of embryos - must occur at places or times where updraughts are weaker.

Further, the kinematic structure of a storm is determined not only by the available thermodynamic instability, but also by the vertical shear of the horizontal wind within the larger-scale environment; thus, it is generally believed that the highly organized storms, called supercells, can occur only in the presence of considerable wind shear.

3.4 Cloud seeding concepts for hail suppression

In cases where hail forms on graupel embryos, the

concentration of graupel can, in principle, be increased by seeding early in the lifetime of new convective cells. A generalized concept of seeding new growth regions for this purpose has emerged independently in several hail projects, despite lack of precision in estimating the subsequent trajectories of such additional graupel particles and in ignorance of whether they in fact would enter the important hail growth regions to compete with the natural embryos.

Important questions have been raised about the required dispersion of the nuclei. For example, line sources (rockets, droppable pyrotechnics and airborne generators) offer an advantage over point sources (exploding shells). However, rockets and shells offer a chance for very rapid response to threatening situations. Also, problems of deactivation of nuclei by sunlight and by wetting in warm cloud have been raised, but these problems can be avoided when the seeding agent is injected directly. When airborne or ground-based generators are used, deactivation can be reduced by careful control of the chemical composition of the seeding agent.

The implementation of the seeding concepts in specific hailstorm situations requires very careful attention to the storm structure. In storms where each cell has a simple vertical structure and the hail embryos grow into hailstones near their place of origin, seeding in each new cell before the natural hail embryos appear offers a possibility of suppressing damaging hail. In more complex and persistent storms, where hail embryos may move in a continuous stream from the embryo growth region to a quite distinct hail

growth region, more subtle techniques are likely to be required. Various authors have proposed seeding "embryo curtains", "shelf clouds", or "under the radar overhang". These concepts may be qualitatively acceptable, and they serve as the basis for many hail suppression operations. These concepts, however, need to be subjected to more rigorous scientific evaluation with the aid of numerical cloud models.

3.5 Evaluation

In spite of very intensive efforts by many groups in many countries, seeding effects have not been clearly identified in the physical parameters of hailstorms. It is therefore still necessary to rely mainly on statistical evaluation of a hail suppression experiment to determine the likelihood that the variations are not simply chance fluctuations. It is desirable to do two kinds of analyses, exploratory and confirmatory. In the exploratory analysis of the experiment, a large number of parameters (hail size distribution, radar parameters, etc.) should be subjected to various statistical tests, with the aim of isolating the most significant and promising variables. For the confirmatory analysis, one of these parameters is chosen and used in a statistical test which is defined a priori.

Crop (or other) damage is ultimately the most relevant parameter, but due to the great variations among crops and their different rates of maturing during the growing season, crop damage is not recommended as a primary response variable.

The relation between the variables derived from hailstone number and sizes (e.g., mass or kinetic energy) and crop damage should, therefore, be better established.

Since there are indications that different kinds of storms in different synoptic situations react differently to a given treatment, it is advisable to use stratification or predictor variables (covariates) which can considerably reduce the variability of the data. There is, therefore, an urgent need to develop such variables which are highly correlated with the test variable.

It is important that studies of all measurable physical effects (significant changes of radar echo characteristics, embryo type, etc.) are made in parallel with the statistical evaluation, because this can lend much credibility to the statistical result. In fact, if a statistical conclusion, even of high significance resulted, but if it were in contradiction to the physical factors, the result might well have to be regarded as inconclusive. It would also be difficult to transfer the results to another region without such physical understanding.

In many regions where hail damage occurs, it is the same storms which produce much of the rainfall needed by agriculture. There is no observational evidence to show whether or not seeding for hail suppression increases or decreases rainfall in the defined target area or in nearby areas.

However, this is a potential problem which needs further investigation and should be built into the design of any future hail suppression experiments.

The optimism regarding hail suppression in the early 1970's and the suggestion of "promising prospects of success in the near future" made in the statement on Weather Modification (see Appendix ...), have not in fact materialized. As knowledge of hailstorms has increased, so has the uncertainty regarding the response to cloud seeding. There is an increasing theoretical basis, and some observational evidence, to suggest that, depending on the embryo type (graupel or frozen raindrop) or on the kinematic characteristics of the storm (multicell, supercell, etc.), the response to seeding may be positive or negative. Thus, WMO has adopted the position of encouraging international co-operation in research aimed at solving the scientific issues as a necessary first step before hail suppression can be put on much sounder scientific basis.

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TROPICAL CYCLONE MODERATION

Tropical cyclones contribute significantly to the annual rainfall of many areas, but they are also responsible for considerable damage to property and for a large loss of life. Therefore, the aims of any modification procedure should be to reduce the wind, storm surge and rain damage, but not necessarily the total rainfall (WMO (1975)).

Recent field experiments in tropical cyclone modification have been directed at reducing peak wind speed. The force of the wind varies with the square of the wind speed; therefore, a reduction of 10 to 15 percent in the maximum winds will result in a reduction of 20 to 30 percent in the maximum force of the winds. Research relating damage to wind speed suggests that a given percentage reduction in wind speed could reduce damage by an even higher percentage. The storm surge is a function of several parameters; the principal influences are the sustained wind speed and the slope of the ocean's bottom. This suggests that in most cases a reduction in the maximum wind speed will also reduce the storm surge. It seems reasonable to suppose therefore, that if we could reduce the maximum surface wind speed by even 10 to 15 percent, tropical cyclone damage could be reduced very significantly and lives might be saved in areas that are difficult to evacuate.

Tropical cyclone modification experiments have been conducted by the United States in the Atlantic Ocean. They are designed to cause a reduction in the maximum wind speeds through an alteration in the location of energy released near the storm's center (Sheets (1973)). A tropical cyclone draws most of its energy from latent heat released during the convective overturning of the atmosphere. At low levels, warm moist air

spirals over the tropical sea toward the storm's center carrying copious quantities of latent and sensible heat. As this air flows into the storm, it acquires additional energy from the warm ocean. Most of this air flows upward into the eyewall, a band of clouds ringing the relatively calm eye, and/or into the surrounding rainband clouds (see Fig. 1). The rising air releases latent heat in these clouds and thus furnishes most of the energy for driving the storm. The air, already turning slowly because of the rotation of the earth before it starts its inward spiral, gathers tangential speed through partial conservation of its absolute angular momentum as it draws nearer the storm's center. This results in winds of destructive violence in the eyewall region before the air moves upward and then away from the storm's core at high levels.

The area of convective-scale ascent of air from the inflow layer to the upper tropospheric outflow layer is small compared to the total area of the tropical cyclone, the typical value of the ratio of the eyewall convective area to the total tropical cyclone area being less than 1 percent. This has important consequences for proposed experiments: 1) only a very small region of the storm need be modified to produce a significant result (i.e., the experiment is logistically feasible), and 2) there is good reason to believe that the location and intensity of the convective-scale ascent (i.e. the eyewall region) can be modified through use of "dynamic seeding".

Dynamic seeding may provide a means of causing changes in the location of the major vertical mass transport. Injection of silver iodide particles into clouds containing supercooled water droplets causes the droplets to freeze and grow, thereby releasing latent heat. This additional heat release in the ascending convective currents increases cloud buoyancy and causes more vigorous and deeper ascending motion. As the air rises, it

expands and cools, and additional water vapor condenses or sublimates; this in turn releases much greater quantities of latent heat, further increasing the buoyancy of the cloud and stimulating cloud growth.

Observations of tropical storms suggest that in most of the areas radially outward from the eyewall there are clouds that can be made to grow rapidly by seeding. The growth of these seeded clouds provides the mechanism for shifting the major vertical mass transport to a larger radius. The reduction in the wind speeds comes naturally from this sequence of events. The air spiraling inward increases in tangential velocity because of the partial conservation of absolute angular momentum until it finally ceases its inward motion and rises. Increased convective activity in the area of seeding offers an avenue by which the inward spiraling air can rise upward to the outflow layer of the storm earlier than would otherwise be the case. Thus, air flowing inward ascends in a new eyewall region before it reaches the tangential speeds that it would have achieved had it spiraled into the old eyewall. As there is no longer a bountiful supply of warm, moist air ascending in the old eyewall, it gradually weakens and dissipates.

Numerical model experiments suggest that creating a new eyewall with reduced maximum winds and dissipating the old eyewall are feasible objectives, and that the new eyewall may prove to be a stable circulation mode for at least a good portion of a day (Rosenthal (1971)). This process is illustrated schematically in Fig. 1 which shows a vertical cross section of the center of the storm where only the translational flow is illustrated. The upper panel shows the storm prior to seeding, the middle panel illustrates the hypothesized alterations in the translational flow and cloud structure, including dissipation of the old eyewall, and the lower panel shows the resultant new eyewall with its greater diameter and reduced maximum winds.

Calculations show, for example, that if the inflowing air can be induced to rise in enhanced convective updrafts at a radius 80 per cent larger than that of the pre existing eyewall, the maximum winds will be reduced 30 per cent.

In 1969 Hurricane Debbie was seeded twice over a period of several hours according to the hypothesis described above, and reductions in peak wind of 15 and 31 per cent were observed by aircraft at 3Km (Gentry (1970), (1974)). Nevertheless, wind speed variations of this magnitude occur naturally in tropical cyclones, and the hypothesis of deliberate modification is not easily proven. In particular, measurements made during these experiments did not allow each of the links in the chain of events described earlier to be verified. Furthermore, while other experiments have been performed, only this single hurricane has so far been seeded over a period of several hours according to the hypothesis described above.

The limited data and experimental sample and the preliminary state of theoretical models mean that it cannot yet be stated with certainty that winds can be reduced by seeding. However, the encouragement offered by the few observations available and the prediction of some models justifies further experimentation. This is particularly true when it is recognized that the growth of population and of investment in cyclone-prone areas increases the destructive potential of tropical cyclones.

Past experiments and model calculations suggest that seeding has only a temporary effect and that the storm returns to its natural configuration within about 12 to 18 hours. Although there is no evidence that seeding has any effect on the direction of motion or the total rainfall of a tropical cyclone, it seems wise to limit experimental seeding to tropical cyclones which are not expected to reach land within 24 hours.

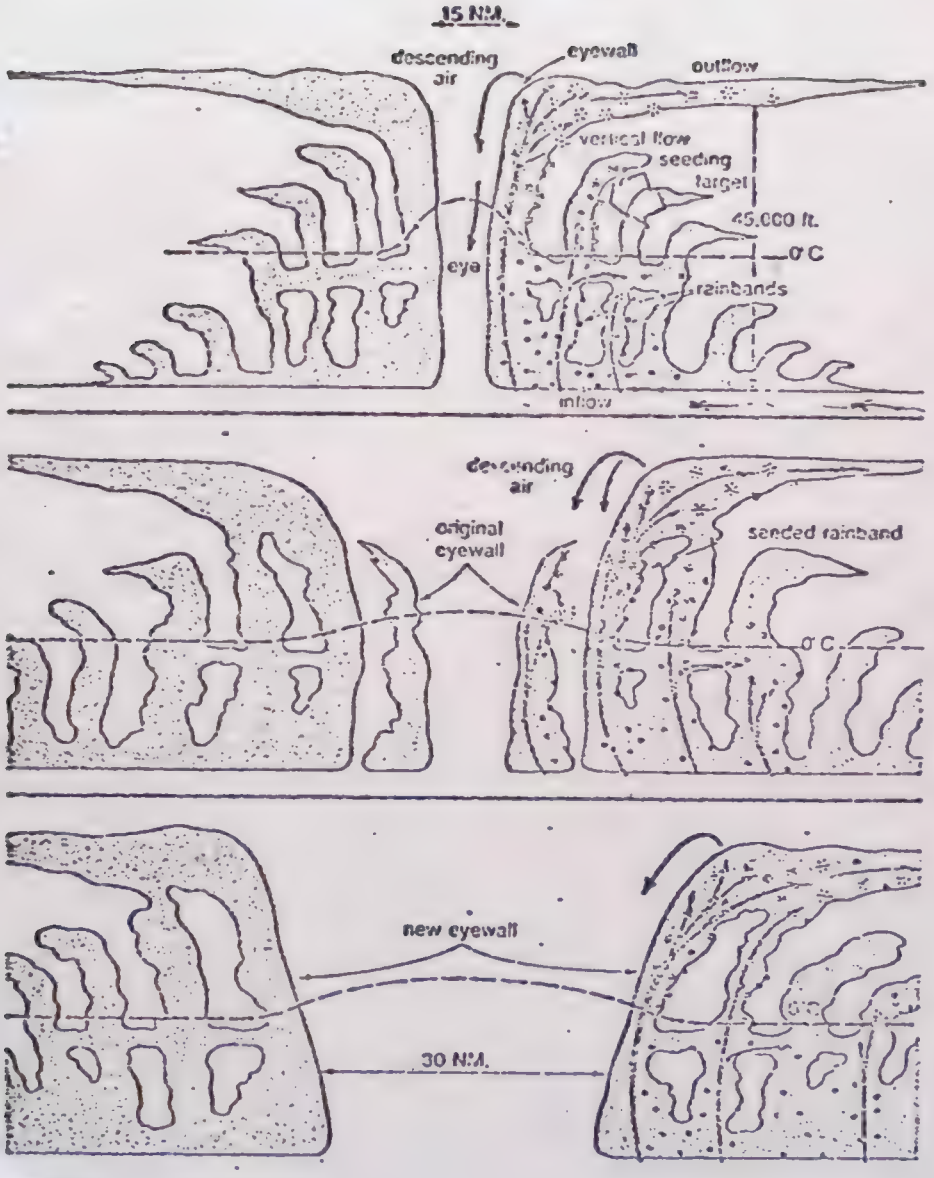

Figure 1 Schematic drawing of the hypothesized convective structure and translational flow through a storm before, during and after seeding effects start to take place.

Because of the many uncertainties that exist to date it is recommended that operational tropical cyclone modification should not be carried out until further experiments have provided the necessary quantitative scientific basis and other complementary studies have demonstrated that real benefits can be achieved for the whole region concerned.

Other techniques and hypotheses have been proposed from time to time for the modification of tropical cyclones. Many of these are described in a report of the United States Weather Modification Advisory Board (1978). These ideas include cooling the sea surface in the storm's path, the use of evaporative suppressants on the sea surface, and the dispersion of fine particles of carbon black in the air which might absorb sunlight and heat the air in the outskirts of the storm. All of these ideas involve alterations of the thermodynamics of the storms which eventually influences their dynamic circulation: none has been subjected to more than elementary calculations to explore their feasibility; none has yet been tested in the field.

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LIGHTNING PREVENTION, THE SUPPRESSION OF FOREST FIRES AND OTHER ASPECTS OF WEATHER MODIFICATION

INTRODUCTION

In addition to precipitation enhancement, fog dissipation, hail suppression and hurricane moderation experiments have been carried out with a view to modifying many other weather phenomena. Possibly most work has been done with a view to suppressing or preventing forest fires by increasing precipitation or by reducing lightning strikes respectively. However, experiments have also been carried out aimed at initiating convective cloud formation, suppressing convective clouds by initiating downdrafts, and producing clouds in ice-supersaturated layers of the atmosphere with the object of preventing the formation of radiation fog. Nearly all these experiments have been exploratory in nature and no techniques satisfactory for operational use have yet been developed.

LIGHTNING PREVENTION

Lightning is one of the major causes of forest fires and is directly responsible for death or injury to many people annually. Two different principles are being explored with a view to reducing the frequency or severity of lightning strikes: discharging the cloud artificially at a controlled rate without waiting for lightning to occur, and decreasing the basic efficiency of the charging mechanism (Dawson *et al* (1974)).

Kasemir (1974) has carried out a number of experiments in which conducting fibres - "chaff" - was dispensed from an aircraft underneath, but close to, the bases of thunderstorms. Corona discharge appears at the ends of a chaff fibre in an electric field of 30KV/m which is more than a factor of ten below the lightning ignition field. The physical concept of the method is that by dispensing large numbers of fibres beneath the cloud the corona current will discharge the growing thunderstorm field well before lightning can occur. Each fibre is capable of generating a corona current of about one microampere and, since about $4X10^6$ fibres weigh only 1kg, relatively small masses of material would appear to be capable of producing significant effects. The experiments appear to have had encouraging results in that electric fields underneath a thunderstorm were found to decay more rapidly with chaff seeding than without and the higher the fields were prior to seeding the more rapid was the decay. However, much more experimental work is required before chaff seeding can be regarded as an effective tool for lightning suppression.

Cloud seeding with AgI or other ice nuclei has also been suggested as a means of preventing lightning, although here the physical hypothesis on which the experimental work has been based has not been clearly stated. Fuquay (1967) suggests that glaciation induced by seeding should increase the within-cloud conduction currents and alter the initiation and nature of cloud-to-ground discharges. As reported by Dawson *et al* (loc. cit.) a limited

number of experiments has been conducted in the US in which clouds have been seeded with a view to reducing lightning strikes: encouraging but not statistically significant results were obtained. Similar work with similar results has been reported by Gaivoronsky et al (1974).

SUPPRESSION OF FOREST FIRES

Cloud seeding has also been used to increase precipitation with the object of suppressing forest fires. It is recognized that quite small amounts of rain can alter a potentially dangerous fire situation to one of comparative safety and that initiating very light rain during critical fire conditions would be very beneficial. Dawson et al (loc. cit.) report some work carried out on this basis and Artsybashev et al (1974) report on attempts in 1970-1972 to extinguish 280 forest fires by seeding clouds upwind of the fires with the intention that they precipitate when over the fire. They report that in 214 cases precipitation followed the seeding and that 121 fires were extinguished. No controls are mentioned so that the statistical significance of the result is unknown.

OTHER ASPECTS

Experiments aimed at producing or suppressing clouds are even more exploratory in nature than is the work reported above. Typical of the work being done is that reported by Bigg and Meade (1971), Dessens (1960) Vulfson and Levin (1974) and Vulfson et al (1976).

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APPENDIX A

STATEMENT ON "PRESENT STATE OF KNOWLEDGE AND POSSIBLE PRACTICAL BENEFITS IN SOME FIELDS OF WEATHER MODIFICATION"

(Approved by the Seventh Congress of WMO, April-May 1975)

1. General

It has been demonstrated that ice crystals may be caused to form in supercooled clouds by seeding them with dry ice, silver iodide and other nucleants. Ice crystals are known to play an important role in the process of formation of precipitation; cloud seeding therefore provides a means of modifying the precipitation process in some types of supercooled clouds. The seeding of a supercooled cloud converts it to ice, releasing latent heat which can have important dynamical effects. The varied and controversial results of seeding experiments appear to be due to the complexities of the dynamics and microphysics of the precipitation process. An encouraging beginning in the understanding of these processes has been made through the development of numerical models which incorporate both the dynamics and microphysics and their interactions. Such models and their successors may be expected to define more clearly the most favourable seeding situations and the observations needed for the evaluation of the results. Although some experiments have apparently yielded positive results, the possible practical benefits of weather modification can be realized only through an increased research effort. This research should be directed primarily at cloud dynamics and mesoscale dynamics and the interactions of dynamics with microphysics, since knowledge of the latter is relatively more complete. There is a great need for simultaneous measurements of dynamical and microphysical parameters.

Some experiments have been made to test the possibility of seeding warm clouds with hygroscopic particles or water droplets in order to increase precipitation. The results obtained from these experiments have not been conclusive or sufficiently positive.

It appears that the most sophisticated statistical procedures are an inadequate substitute for more complete knowledge of the atmospheric mechanisms. However, statistical design and evaluation of experiments are both necessary to increase our understanding of physical aspects in the further development of weather modification, particularly in connexion with the evaluation of the practical results of experiments.

It is important to emphasize that weather modification is still largely at the research stage. For this reason, operations should be undertaken only after the most careful study by experts of the particular situation, and on the understanding that the desired end results may not always be achieved.

Brief summaries of the current status of weather modification in several categories are given below.

2. Stimulation of precipitation

Of the many experiments conducted in this field, only a few have clearly demonstrated that seeding has increased the precipitation; in some cases, there is evidence of a decrease. However, these apparent contradictory results seem to emerge from the fact that, in different geographical locations, clouds have different cloud-droplet spectra and different ice-crystal properties and concentrations. There is some evidence that winter-time orographic precipitation can be somewhat increased over mountain ranges. Similar results have also been obtained in sub-tropical, continental cumulus clouds in winter.

There is some evidence that certain sub-tropical convective clouds become taller and larger, with a tendency to merge, when they are heavily seeded to release latent heat.

In view of the high correlation between the size of convective clouds and the rainfall from them, the seeded clouds presumably give more rain than if they had not been seeded. Confirmation is required from further suitably designed experiments.

3. Dissipation of fog

Supercooled fog and stratus can be dissipated by growth and sedimentation of ice crystals, induced by seeding the fog with ice nucleants or by means of cooling agents. This has been brought into operational use at several airports at which there is a relatively high incidence of supercooled fog. The more common warm fog may be dissipated by the use of heat, hygroscopic particles and the down-wash of helicopters. Successful experiments have been reported with each of these techniques, but only the use of heat seems operationally viable at present.

4. Hail suppression

Many countries have focused considerable attention on hail-suppression projects in the last decade or so. In spite of the complexity of the hail-forming processes and the extremely large variability in hail occurrence which make hail suppression experiments very difficult to assess, there appear to be promising prospects of success in the near future.

Impressive reports of successful reduction in hail damage to crops, with resulting economic benefit, have provided impetus to many experiments and large mainly operational projects. As yet, there are no universally recognized methods and the results to date are not unambiguous. The seeding methods produce different effects on different storms, and it is essential that detailed understanding of the structure and the processes of various types of storms be obtained so that seeding procedures specially tailored to the specific atmospheric conditions can be determined. The development of numerical models is of great importance for the future understanding of the processes within cumulonimbus clouds. These models should

incorporate proper dynamics and thermodynamics with details of the microphysics and water phase transition processes and their interaction. This approach should be tested against detailed direct measurements of cloud properties.

More basic research is required to resolve questions on various hailstorm theories, models and suppression techniques. Development of more reliable evaluation methods based on both physical and economic indicators is also needed.

5. Hurricane modification

The seeding of hurricanes has been followed by reduced maximum wind velocities. Confirmation is required from further experiments which should include an increased number of measurements in pertinent regions of the storm. This is because assessment will largely depend upon physical methods, rather than statistical ones. There is also need for improved numerical hurricane models to provide guidance for future experiments.

6. Other aspects

Exploratory investigations are being conducted into the suppression of forest and bush fires, the inducement of down-droughts in developing convective clouds and the prevention of lightning. Attempts are also being made to seed cold ice-supersaturated layers of the atmosphere, in order to produce clouds, with the object of preventing the formation of radiation fog.